

TPV cell IV curve testing with varying black body emission temperatures, intensities, and cell temperatures

James J. Lin and Dale R. Burger
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91109

Abstract: A TPV GaSb cell was tested as part of an effort to establish a standard method of characterizing such cells. Cell current/voltage (IV) curves were measured at different cell temperatures using black body radiation at various emission temperatures and intensities. The results of the effects on performance are briefly analyzed and include temperature coefficients, voltage/intensity coefficient, and response to spectral shift.

Thermophotovoltaics (TPV) is an energy conversion method which converts heat into electricity. This is achieved by first converting heat into photons via a thermal emitter. Photons from the thermal emitter are in turn converted to electricity via TPV cells. These cells are similar to ordinary photovoltaic (PV) cells except that they are fabricated to have a bandgap which corresponds to the peak emission spectrum of the emitter. With an emitter with high emissivity and a bandgap matched TPV cell, the efficiency of a TPV system is expected to be higher than that for conventional PV. Bandgap matching assures the cell of receiving the most useable radiation for conversion to electricity. Efficiencies as high as 50% for a TPV system incorporating silicon cells and 35% for other TPV systems are theoretically possible^{1,2}.

In this letter, we present results of testing TPV cells and our findings concerning repeatability, temperature coefficients, intensity effects, and spectral shifts. This letter discusses testing procedures for current/voltage (IV) curves and their results.

Although the concept of TPV has been around for some time, no one has yet defined a standardized method for characterizing TPV cells. Now that commercial TPV systems are being actively designed, there is a growing need to establish testing standards. One possible solution is to test TPV cells with black body emissions. A black body is a nearly perfect emitter and the emitted radiation follows the spectral distribution curve defined by Planck's equation. Black bodies are readily available so that tests may be reproduced elsewhere. A black body emitter can be set at different operating temperatures to vary the emission spectrum. Detailed knowledge of the emission spectrum and its variations is generally lacking in all of the previous TPV test programs found in the literature. Testing with varying emission spectra is required for accurate prediction of performance at different system operating temperatures.

Furthermore, for a given black body emission, the intensity should be varied. Since cell series resistance losses are current dependent, output power and current are non-linear with

intensity. The open circuit voltage is also dependent on the logarithm of the intensity thus making intensity corrections necessary. IV curves of a TPV cell must furthermore be taken at different cell temperatures, since performance will change. Testing with the three variables of black body emission temperature, intensity, and cell temperature produces many of the results required for complete TPV cell modelling and performance prediction.

We have tested TPV cells with black body radiation at different emission temperatures, intensities, and cell temperatures. A GaSb cell supplied by JX Crystals was used for this test.^{a)} The test cell was exposed to black body emissions at temperatures of 1200°C and 900°C. Note that the black body temperatures are only expected to be accurate to within 10°C by manufacturer specification. The intensity was varied by placing the cell away from the black body source at distances of: 0.5", 1.5", and 2.5" respectively. These three locations produced intensities of 1.28, 0.303, and 0.141 W/cm², or 4.8%, 1.1%, and 0.53% respectively of full black body intensity at 1200°C. Only the first position, 0.5", was selected for testing at 900°C black body temperature; its intensity was 0.458 W/cm², or 4.4% of full intensity. Intensities were measured with a radiometer and calculated using an optical model furnished by the manufacturer. The radiometer readings were used even though they were accurate only to within 15% even after calibrating with another radiometer. The emission spectrum and intensity should be repeatable with a standard black body and radiometer. Accuracy can be improved with further calibrations and use of better equipment when it is funded.

To vary cell temperature, a water circulating bath was used to cool the cell. The water temperature was varied from 8°C to 40°C, and was accurate to within 1°C as measured with both a thermometer and a thermocouple. For intensities of 1.28, 0.458, 0.303, and 0.141 W/cm², the cell temperature would only be 2°C, 0.7°C, 0.5°C, and 0.2°C respectively, higher than the cooling water temperature. This was both measured and calculated by heat conduction equations.

The current/voltage (IV) tests for the TPV cells indicate that they are repeatable. For exactly the same test performed consecutively, within minutes apart, the repeatability was within +/-1%. For the same tests performed on different days, the repeatability was within +/-2%. Tests performed on different days represent totally separate tests since all the equipment had to be reset. The repeatability applies to the IV short circuit current (Isc), open circuit voltage (Voc), peak power (Pmax), and fill factor ratio (FF).

The overall 2% repeatability is certainly better than the accuracy of the testing system. The test system must then be consistently repeating. The black body has an accuracy of 10°C,

^{a)} Please note that this cell was not necessarily a representative sample of JX Crystals's products since we could not guarantee its return in good condition.

corresponding to a maximum intensity error of 2.8%. The radiometer intensity readings have a maximum possible error of 15%. Readings from the IV data logger are calibrated to an accuracy of 0.5%. Even though the results are repeatable to 2%, the absolute accuracy of the present set of test results can be off by as much as 20% due to total systems error. Further equipment improvements and calibrations should be able to increase this accuracy. The repeatability of the tests does demonstrate that this TPV testing procedure is a potentially valid method for standardized testing. Since the repeatability was good, some additional data analysis was performed.

First, an analysis was performed on the effects of cell temperature on the most stable cell parameter, Voc. Temperature coefficients are calculated by taking the changes in performance divided by the change in cell temperature. Thus, Voc temperature coefficients were obtained by taking the slope of the first order regression line of Voc versus cell temperature. This was taken for data at three different intensities and two different black body temperatures. One data point at 8°C and 0.5" distance for the 1200°C black body was dropped due to poor fit. After dropping the one point, all four of the R values (square root of the coefficient of determination) were better than .9945. The average of the Voc temperature coefficients was -0.001205 V/°C with a range of -0.00114 to -0.00127 V/°C. Data points and regression lines are shown in Figure 1. Note that each plotted data point represents the average of at least three separate test runs made just minutes apart. It is obvious from Figure 1 that Voc is dependent upon intensity as well as temperature.

A plot of Isc versus cooling water temperature was made next and is shown in Figure 2. It was obvious that, unlike the Voc temperature coefficient, the Isc temperature coefficient has an intensity dependence; it is linearly dependent on the intensity at a specific black body temperature. To normalize this for all intensities, the Isc temperature coefficients were scaled by dividing by its corresponding Isc output for that intensity: these are percentage temperature coefficients. Using this approach, the average for the 1200°C black body values is 0.31 %/°C with a range of 0.37% to 0.24%. Since the Isc temperature coefficient was not well behaved, the Pmax data was not analyzed.

The temperature coefficients found are limited to the temperature and intensity range tested. The Voc and Isc temperature coefficients are valid within a cell temperature range of 10-40°C and is limited to the tested intensities of 0.141 - 1.28 W/cm². From this analysis, it was found that the Voc temperature coefficient was extremely stable for the cell at different intensities and black body temperatures. The Voc temperature coefficient was linear over the tested temperature range. The Isc temperature coefficient was dependent upon the intensity and the black body temperature.

The dependence of Voc on intensity was determined next. Theory shows that Voc has a logarithmic dependency on intensity. For a 1200°C black body emission temperature, this relation was found to be:

$V_{oc} = .129 * \log_{10}(\text{intensity W/cm}^2) + (\text{temperature constant})$. The temperature constants are .366, .352, and .341 Volts for 10°C, 20°C, and 30°C cell temperatures respectively (See Figure 3). Since the V_{oc} temperature coefficient was known, it was used to correct the V_{oc} at water bath temperatures to actual V_{oc} at listed cell temperatures, for data points in Figure 3. Intensity constants are limited to 1200°C black body, the tested intensity range, and cell temperatures. The constants for the logarithmic dependency obviously cannot be predicted from results taken at only one intensity.

Furthermore, the power output was analyzed. The respective peak power outputs at the three locations, 0.5", 1.5", 2.5", were 9.33, 1.978, 0.731 mW for the 1200°C black body temperature, at 10°C cell temperature. While the intensity at 0.5", is 4.2 and 9.1 times greater than that at 1.5" and 2.5" respectively, the peak power is 4.7 and 12.8 times greater. Thus, as the intensity increases, efficiency increases. However, this is nonlinear as well as non-logarithmic. This test is then especially important for TPV cells typically operating with high intensities (50-200 suns).

Testing with different black body temperatures demonstrated the effect of a spectral shift on performance. With the black body at 900°C, the intensity of the emission is reduced by a factor of (T_2^4/T_1^4) , using absolute temperatures. At the 900°C black body temperature the emission intensity should be 40.2% of that at 1200°C. However, the measured I_{sc} output at 900°C was only 19.7% of the I_{sc} at 1200°C. This disparity agrees with the expected effect of a spectral shift on performance for the cell under test. The bandgap of GaSb is .69 eV (1.73×10^{-6} m), for the tested cell temperature range. The peak wavelengths for black body emission at 1200°C and 900°C are 1.97×10^{-6} m and 2.47×10^{-6} m respectively, and are both lower in energy than the bandgap of the cell. Thus, much of the photon energy is not available for conversion to electricity. By reducing the black body emission temperature, a greater percentage of the energy is lost due to spectral shifting because the peak wavelength of the emission is now further away from the bandgap of the cell. Actual quantitative results of performance for different emission spectra cannot be predicted simply from the performance at a single spectrum. Two or more black body temperatures are required in order for any quantitative comparison and performance prediction. More exact performance predictions are possible with spectral response tests of the cell. Spectral response tests at different cell temperatures are planned to be completed at a later date and may be reported at that time.

In conclusion, the research proves that the described TPV cell testing procedure is repeatable and an identical or similar procedure is necessary for complete TPV cell characterization. Repeating these tests at another laboratory would simply require a black body with the same or better temperature capabilities and a radiometer for intensity measurements. Repeating cell water cooling temperatures with a water circulator is simple enough. The tests demonstrated the need for varying black body temperatures to determine the results of spectral shifts, varying

TPV cell temperatures to determine temperature coefficients, and varying intensity to determine the Voc intensity coefficients. For complete TPV cell characterization, spectral response testing, reverse IV curves, and possibly radiation effects testing would be necessary to supplement the described TPV IV testing.

The authors would like to acknowledge Dr. C. R. Lewis and R. L. Mueller for their insight and support into TPV research and I. W. Fraas for providing the GaSb cell used for testing. The work described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, and was supported by the Department of Energy, Knolls Atomic Power Laboratory.

References

- 1 W.E. Home, A.C. Day, and L. Crabtree. "Improved Thermophotovoltaic Power System," Proc. of 17th IECEC, v1, pp 119-124, 1982.
- 2 L.D. Woolf, "Optimum Efficiency of Single and Multiple Bandgap Cells in Thermophotovoltaic Energy Conversion," Solar Cells, v19, pp 19-38, (1986-1987).
- 3 L. M. Fraas, et. al., "Fundamental Characterization Studies of GaSb Solar Cells," Proc. of 22nd IEEE PVSC, Aug. 1991, v1, pp 80-84.

FIG. 1₀
linear dependency of Voc on cell temperature for various
emission intensities and temperature.
Voc temp. coefficient = $-1.2 \text{ mW/}^{\circ}\text{C}$

FIG. 1

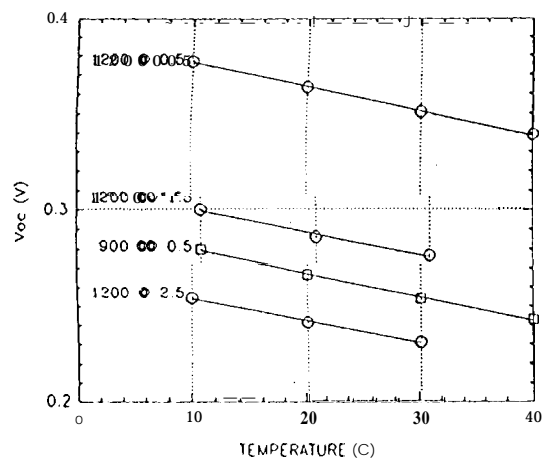


FIG. 2.
Linear dependency of I_{sc} on cell temperature for various
emission intensities and temperature.
 I_{sc} temp. coefficient $\approx 0.31\ \%/^{\circ}\text{C}$

Fig. 2

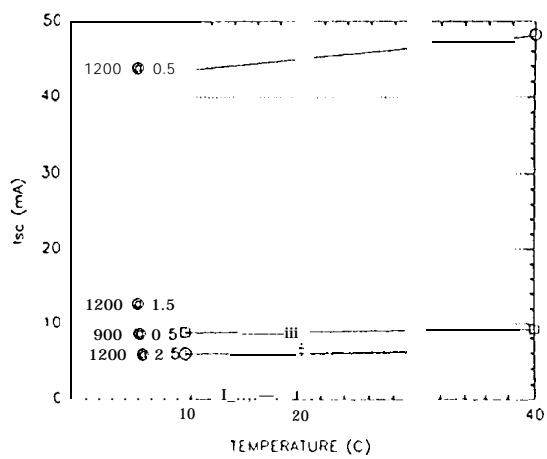


FIG. 3.

Logarithmic dependency of Voc on emission intensity at various cell temperatures.

$V_{oc} = .129 \log(\text{intensity W/cm}^2) + \text{temp. constant}$

Temp. constants = .366, .352, .341 V for 10°, 20°, 30°C cell temperature.

Fig. 3

